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EXCESS NUTRIENTS IN HYDROPONIC SOLUTIONS ALTER NUTRIENT CONTENT OF RICE, WHEAT, AND POTATO

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ABSTRACT

Environment has significant effects on the nutrient content of field-grown crop plants. Little is known, however, about compositional changes caused by controlled environments in which plants receive only artificial radiation and soilless, hydroponic culture. This knowledge is essential for developing a safe, nutritious diet in a Controlled Ecological Life-Support System (CELSS). Three crops that are candidates for inclusion in a CELSS (rice, wheat, and white potato) were grown both in the field and in controlled environments where the hydroponic nutrient solution, photosynthetic photon flux (PPF), and CO_2 level were manipulated to achieve rapid growth rates. Plants were harvested at maturity, separated into discrete parts, and dried prior to analysis. Plant materials were analyzed for proximate composition (protein, fat, ash, and carbohydrate), total nitrogen (N), nitrate, minerals, and amino-acid composition. The effect of environment on nutrient content varied by crop and plant part. Total N and nonprotein N (NPN) contents of plant biomass generally increased under controlled-environment conditions compared to field conditions, especially for leafy plant parts and roots. Nitrate levels were increased in hydroponically-grown vegetative tissues, but nitrate was excluded from grains and tubers. Mineral content changes in plant tissue included increased phosphorus and decreased levels of certain micronutrient elements under controlled-environment conditions. These findings suggest that cultivar selection, genetic manipulation, and environmental control could be important to obtain highly nutritious biomass in a CELSS.

INTRODUCTION

Sustainability of a space-deployed controlled ecological life-support system (CELSS) will require the production of safe, nutritious foods. To address issues of food safety and nutritional adequacy of diets, the composition of plant biomass produced for human consumption must be known and controllable. Data on this subject relevant to CELSS are inadequate. Nutritional data for field-grown crops are available in the literature, but generally not for the specific cultivars studied by CELSS investigators, and only for plant parts traditionally eaten. While significant attempts have been made to optimize growth conditions in controlled environments to increase yields of the CELSS candidate crops rice, wheat, and potato /1-9/, little information is available on their nutrient composition /10/. The nutrient composition of crops grown in the field may differ from that of crops grown in controlled environments, where water, temperature, and nutrient stresses ideally should be minimal. Nutrient composition data provide feedback to CELSS researchers as they optimize conditions for crop production and genetically modify nutrient composition. Data also are needed to develop food products from edible crop biomass and to design appropriate diets. Therefore, we evaluated effects of growth environment on the composition of edible and inedible plant parts of rice, wheat, and potato.

TABLE 1 Planting and harvest information for rice, potato, and wheat grown in controlled environments

	Rice	Potato	Wheat	Wheat
Location	Purdue University	Kennedy Space Center	Kennedy Space Center	Utah State University
Environment	Growth Chamber	Biomass Production Chamber	Biomass Production Chamber	Growth Chamber
Cultivar(s)	'Ai-Nan-Tsao'	'Norland'	'Yecora Rojo'	'Yecora Rojo' 'Veery-10'
Harvested: Days After Planting	85 days	105 days	85 days	64 days after emergence
Plant Parts	Grain, Vegetative[1], Roots	Grain, Vegetative[1], Roots[2]	Grain, Chaff, Straw, Roots	Grain, Chaff, Straw[3]
Culture[4]	recirculating hydroponic solution, deep root zone, modified 1/2 Hoagland solution, nitrate as only source of nitrogen	recirculating nutrient film technique, modified 1/2 Hoagland solution, nitrate as only source of nitrogen	recirculating nutrient film technique, modified 1/2 Hoagland solution, nitrate as only source of nitrogen	recirculating hydroponic solution, deep root zone, modified 1/2 Hoagland solution, nitrate as only source of nitrogen
Photoperiod (hours light per 24 hour day)	10 hours light	12 hours light until day 65, 16 hours light after day 65	20 hours light	24 hours light
Lamp Type	fluorescent and high-pressure sodium	high-pressure sodium	high-pressure sodium	high-pressure sodium
Photosynthetic photon flux	655 $\mu mol \cdot m^{-2} s^{-1}$	850 $\mu mol \cdot m^{-2} s^{-1}$	750 $\mu mol \cdot m^{-2} s^{-1}$	1200 $\mu mol \cdot m^{-2} s^{-1}$
Temperature	32°C light/ 26°C dark	20°C light/ 16°C dark through day 40, then constant 16°C	24°C light/ 20°C dark until day 16, then 20°C light/ 16°C dark	23°C constant
Relative Humidity	72 ± 5%	75%	75%	70%
Carbon Dioxide	1500 ppm	1200 ppm	1200 ppm	1000 ppm

[1] Vegetative = leaves and stems

[2] All plant parts are specified in the text as BPC-1 or BPC-2, referring to the level in the biomass productions chamber (BPC) on which plants were grown. Level 1 had no air filtering. Level 2 had charcoal and permanganate air filtering.

[3] All plant parts are specified in the text as RF (Right Front) or LR (Left Rear), indicating the areas in the growth chamber from which samples were taken for analysis.

[4] See Table 2 for concentrations of elements in nutrient solutions.

TABLE 2 Initial concentration of elements in the nutrient solutions for growth chamber rice from Purdue University, growth chamber wheat from Utah State University, and biomass production chamber wheat and potato from the Kennedy Space Center

Element	Growth Chamber Rice[1]			Growth Chamber Wheat[2]			Biomass Production Chamber Wheat and Potato[2]	
	Starter	Pre-Anthesis	Post-Anthesis	Starter	Pre-Anthesis	Post-Anthesis	Starter	Replenishment[3]
	Concentration, mM							
NO_3-N	4.09	4.02	3.01	4	4	3	7.5	75
NH_4-N	0.06	----	----	----	----	----	----	----
PO_4-P	0.6	0.5	0.5	0.6	0.5	0.5	0.5	7.5
K	2.7	3.1	2.55	3.75	3.65	2.5	3	68
Ca	1	1	0.5	1	1	0.5	2.5	7.5
Mg	0.5	0.25	0.25	0.5	0.25	0.25	1	9.8
S	0.53	0.5	0.25	1	0.75	0.25	1	9.8
	Concentration, µM							
Fe	130	15	7.5	45	10	10	50[4]	199
B	2	1	1	2	1	0.1	9.5	87
Mn	3	3	3	3	3	3	7.4	68
Zn	3	1	1	3	1	1	0.96	8.8
Cu	0.3	0.1	0.1	0.3	0.1	0.1	1.04	9.5
Mo	0.09	0.03	0.03	0.09	0.03	0.03	0.01	0.1
Si	50	50	25	75	75	----	----	----

[1] Ammonium nitrate solution (57.1 mM NH_4NO_3,, 100 mM HNO_3) or 1 NH_2SO_4 added to control pH between 5.3 and 5.9.
[2] HNO_3 added as needed to control pH to ≈ 5.8.
[3] This solution was added to the working nutrient solution to maintain an electrical conductivity of 0.12 $S \cdot m^{-1}$. Slight variations in the concentrations of specific nutrients were made over the course of the studies.
[4] Initial Fe concentration for wheat was 100 µM.

MATERIALS AND METHODS

Plant Growth, Harvest, and Handling

Rice (*Oryza sativa* L.) cultivar 'Ai-Nan-Tsao', wheat (*Triticum aesitivum* L.) cultivars 'Yecora Rojo' and 'Veery-10', and potato (*Solanum tuberosum* L.) cultivar 'Norland' were grown under both field and controlled environment conditions. Field rice and potato were grown in the summer of 1993 at the Purdue University O'Neall Research Center, in soil fertilized prior to planting with 504 kg ha^{-1} of 19-19-19 NPK (high fertility). Crops were planted in triplicate plots of 2.25 m^2 and were watered as necessary. Plants were pooled by plot upon harvest at maturity and stored in plastic bags on ice until they were washed with distilled water and separated into plant parts. Samples were freeze dried (except rice grain, which was air dried), then ground first with a Wiley mill to pass a 3-mm screen, then with a Udy-Cyclone mill to pass a 1-mm screen. Wheat grown in the field at Utah State University was harvested at maturity, separated into appropriate parts, air dried, and ground as described above. Controlled-environment crops were grown and harvested as reported in Tables 1 and 2. Plant parts were air dried (wheat) or freeze dried (potato and rice, except for rice grain), then ground as described.

Analysis of Plant Materials

Ground, triplicate samples were dried using a vacuum oven (AOAC Method 925.09) /11/, so that all data could be corrected for moisture content and expressed on a dry-weight basis (dwb). Samples also were analyzed in triplicate for ash content using a muffle furnace (AOAC Method 923.03) /11/, as well as for fat content by Soxhlet extraction with petroleum ether (AOAC Method 920.39B) /11/.

The standard micro-Kjeldahl procedure (AOAC Method 960.52) /11/ measures both protein N and some nitrate N, and therefore alone it is not appropriate for determining the true protein content of plant materials that have a significant fraction of N as nitrate /12/. Therefore, protein N content was determined in duplicate after precipitating protein with 6% trichloroacetic acid (TCA) /13/, and then measuring N content of the washed pellet by the micro-Kjeldahl method (AOAC Method 960.52)/11,14/. Total N content was determined in duplicate as described by Goyal and Hafez /12/, using a predigestion procedure to include NO_3-N in the Kjeldahl digestion. Total NPN content was calculated as the difference between total N and TCA-N. Nitrate analysis was performed by the HPLC method of Thayer and Huffaker /15/. Nonnitrate NPN content was calculated as the difference between total NPN and nitrate N. All percent N values were multiplied by the factor 6.25 to obtain percent protein. While it is recognized that other conversion factors have been established for certain plants (e.g., 5.83 for wheat whole grain), the 6.25 factor was used for all plant materials because more appropriate factors have not been determined for controlled environment-grown materials and for inedible parts of plants.

Total carbohydrate content was calculated by difference using the TCA-N method to measure protein: % carbohydrate = 100% - (% ash + % fat + % protein). Mineral analysis was performed on triplicate ashed samples by Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES), as described by McKeehen /14/. Amino acid analysis was performed according to standard hydrolysis and chromatography procedures by a commercial laboratory (AGP Limited, Courtland, Minnesota).

Data from proximate analyses and total N determination were analyzed using multiple t tests of independent samples with unequal variance as described by Steel and Torrie /16/.

RESULTS AND DISCUSSION

Proximate Composition

Comparison to literature values. The proximate composition data of field-grown rice, wheat, and potato (Table 3) can be compared to USDA Handbook No. 8 values /17/ of protein, fat, ash, and carbohydrate contents (%, dwb) for rice grain (8.5, 2.2, 1.4, and 87.9%, respectively), wheat grain (16.1, 2.5, 2.0, and 79.4%, respectively), and potato tubers (10.4, 0.5, 4.5, and 84.6%, respectively). Note that protein values reported in Table 3 are based on the assay for total N. Note also that handbook values above have been converted to a dry-weight basis, to allow for direct comparisons. For example, hard red spring wheat grain USDA Handbook No. 8 values are 13% moisture and 14.0 g protein/100 g, yielding 16.1% protein, dwb. The field-grown rice grain and potato tuber data reported in Table 3 are in reasonable agreement with handbook values. However, the protein content of our field-grown wheat grain was higher than the handbook value, but this high protein can occur in well fertilized field environments /18/.

Protein content based on protein N. When plants were grown in high-N, hydroponic culture, there was an increase in protein N content of all rice plant parts, potato roots/stolons, and some samples of wheat grain, chaff, and straw (Table 4). The protein contents of biomass production chamber (BPC)-grown 'Norland' potato tuber (~6.5%, dwb) and 'Yecora Rojo' wheat grain (18.9%, dwb), as determined here by the TCA-N method, were lower than those reported for potato tuber (15.2%, dwb) and wheat grain (20.9%, dwb) of the same cultivars using the standard Kjeldahl procedure /19/. These differences are explained by the high levels of NPN in potato tubers /20/ and wheat grain (Table 4). The protein content of field-grown wheat grain was lower for 'Yecora Rojo' (16.7%, dwb) than for 'Veery-10' (18.6%, dwb), but growth chamber (GC)-grown wheat grain was higher for 'Yecora Rojo' (18.9% and 20.1%, dwb) than for 'Veery-10' (16.5% and 15.8%, dwb) (data not shown in Table 3 for 'Veery-10').

TABLE 3 Proximate composition of rice, wheat, and potato grown in the field, growth chamber (GC), and biomass production chamber (BPC)[1,2]

			Proximate Composition (%, dwb)			
Crop	Plant Part	Condition	Protein[3]	Fat	Ash	Carbohydrate
Rice 'Ai-Nan-Tsao'	Grain	Field	10.7[b]	2.4[b]	1.7[b]	85.2
		GC	17.0[a]	3.1[a]	1.9[a]	78.0
	Vegetative[4]	Field	4.5[b]	1.7[a]	20.6[a]	73.2
		GC	21.2[a]	1.7[a]	16.1[b]	61.0
	Roots	Field	2.6[b]	2.9[a]	41.0[a]	53.5
		GC	20.8[a]	1.4[a]	19.9[b]	57.9
Wheat 'Yecora Rojo'	Grain	Field	23.2[ab]	1.5[a]	1.9[b]	73.4
		GC-RF[5]	25.8[a]	1.8[a]	1.9[b]	70.5
		GC-LR[5]	25.2[a]	1.1[b]	1.8[c]	71.9
		BPC	22.3[a]	1.4[a]	2.3[a]	73.9
	Chaff	Field	8.9[b]	1.1[a]	13.9[a]	76.1
		GC-RF	12.1[a]	0.7[b]	4.0[c]	83.2
		GC-LR	13.2[a]	1.1[a]	3.2[d]	82.5
		BPC	13.2[a]	1.1[a]	6.0[b]	79.7
	Straw	Field	5.5[c]	1.0[b]	11.0[b]	82.5
		GC-RF	14.4[b]	1.0[b]	10.7[c]	73.9
		GC-LR	13.2[b]	1.5[a]	9.5[d]	75.8
		BPC	23.3[a]	1.7[a]	16.1[a]	58.9
	Roots	BPC	33.3	0.4	10.9	55.4
Potato 'Norland'	Tuber	Field	12.0[c]	0.5[b]	6.1[ab]	81.4
		BPC-1[6]	15.8[b]	1.5[a]	6.1[b]	76.6
		BPC-2[6]	20.0[a]	2.1[a]	7.0[a]	70.9
	Vegetative[4]	Field	17.2[c]	3.4[a]	29.5[a]	49.9
		BPC-1	24.3[b]	2.8[b]	23.4[a]	49.5
		BPC-2	25.0[a]	3.0[ab]	23.4[a]	48.6
	Roots/ Stolons	Field	9.2[b]	4.1[a]	32.0[a]	54.7
		BPC-1	26.6[a]	0.1[b]	14.8[b]	58.5
		BPC-2	26.5[a]	2.2[a]	16.6[b]	54.7

[1] Mean field values are averages of three plots, with at least two protein determinations and three fat and ash determinations from each field plot. Mean GC and BPC values are from at least two protein determinations and three fat and ash determinations from one run in the GC and BPC. Carbohydrate content was calculated by difference.

[2] Means within each plant part having a common letter are not significantly different by t tests (unequal variances), p>0.05. The t-tests compared each controlled environment with the corresponding field environment.

[3] Protein content determined by total N x 6.25. Note that not all N is protein N, as described in Table 4.

[4] Vegetative = leaves and stems.

[5,6] See Table 1 for explanation.

Fat and ash contents. Although the fat contents of some plant parts were significantly different between field and controlled-environment conditions, the fat contents of these crops typically are low and relatively unimportant. Ash content varied among chamber-grown materials and among all environments. Ash contents of field and controlled environment materials are difficult to compare due to possible soil contamination of field samples, especially stems, leaves, and roots. However, the increased ash content of BPC wheat plant parts compared to those from the GC is probably due to higher concentrations of minerals in the BPC nutrient solution (Table 2).

Nitrogen Allocation

Total N. Total N content increased for all plant parts of all crops grown in controlled environments relative to the field, except for 'Yecora Rojo' BPC wheat grain, 'Veery-10' GC wheat grain, and 'Veery-10' GC wheat chaff (Table 4; data not shown for 'Veery-10' wheat). The increase is believed attributable to luxuriant uptake of N by the hydroponically-grown plants.

Accumulation of nonprotein N, including nitrate. Total N and protein N values are best compared by noting the estimate of total NPN. Total NPN content was quite high for a number of the typical inedible plant parts grown in controlled environments, including rice vegetative material, BPC wheat straw and roots, and BPC potato vegetative material and roots. Hydroponic solutions are supplied N in the form of nitrate, and vegetative material is known to accumulate nitrate and other NPN /21/. Nitrate was found to account for a large amount of the NPN in these CELSS crops, particularly in vegetative parts. The nitrate concentration in wheat tissue increased with increasing N concentration in the hydroponic solution (GC vs. BPC). However, even for BPC wheat straw which had nitrate levels 130 times higher than the nitrate level in straw from well fertilized field-grown wheat, nitrate was still excluded from the grain. Similarly, nitrate was high in vegetative material and roots of BPC potatoes, but was almost completely excluded from the tubers. Rice also excluded nitrate from the edible grain. High nitrate consumption by humans can lead to methemoglobin formation, which reduces the ability of the blood to carry oxygen /22/, and may cause the formation of carcinogenic nitrosamines /23/. Unlike the leaves of other CELSS crops such as lettuce and cowpea, the leaves, stems, and roots of rice, wheat, and potato may indeed be inedible because of taste, toxic constituents, and poor digestibility. Thus, excess nitrate in hydroponic solutions and in rice, wheat, and potato tissue may not be a human safety concern because nitrate accumulates only in their inedible plant parts. For CELSS crops that accumulate nitrate in edible plant parts /24/, it may be necessary to control nitrate application and monitor nitrate content of the biomass. In cases in which traditionally inedible biomass is incorporated into novel food products, the nitrate present should be readily leachable from biomass during food and waste processings due to its highly water-soluble nature.

The nonnitrate NPN in plants typically includes nucleic acids and low molecular weight organic N compounds such as amino acids, amides, and peptides /20,25/. Nonnitrate NPN is physiologically and nutritionally important. It is apparent that the ample N in hydroponics alters the amount of this fraction. We plan further studies to characterize the nonnitrate NPN in controlled-environment plants.

Amino acid contents. With very few exceptions, the content of all amino acids of field-grown rice grain, wheat grain, and potato tubers in this study (data not shown) were in the range of values reported in the literature for these crops /26/. Rice grain, wheat grain, and potato tuber amino acid contents followed the same trends as reported for the protein contents of these plant parts grown under field and controlled environments. Rice grain protein N and the content of amino acids increased in growth chamber material relative to the field material, but the limiting amino acid, lysine, did not change as a percent of the total protein. Growth environment had little effect on the amino acid levels of 'Yecora Rojo' wheat grain. Lysine was the limiting amino acid for wheat grain from all growth conditions. The BPC potato tubers had considerable increases in aspartic acid, glutamic acid, and methonine contents relative to field tubers, but the limiting amino acids lysine and threonine did not change as a percent of the total protein.

For rice, wheat, and potato there were no reductions in the proportions of the limiting amino acids in materials grown in controlled environments with high N as compared to field materials. Such reductions

TABLE 4 Percent protein (% nitrogen x 6.25) as derived from total N, trichloracetic acid (TCA)-precipitated N, total nonprotein N (NPN), nitrate N, and nonnitrate NPN for rice, wheat, and potato grown in the field, growth chamber (GC), and biomass production chamber (BPC)[1,2]

Crop	Plant Part	Condition	1 % Protein from Total N	2 % Protein from TCA-Precipitated N	3 % Protein from Total NPN[3]	4 % Protein from Nitrate N	5 % Protein from Nonnitrate NPN[4]
Rice	Grain	Field	10.7[b]	9.5[b]	1.2	0.0	1.2
'Ai-Nan-Tsao'		GC	17.0[a]	16.6[a]	0.4	0.0	0.4
	Vegetative[5]	Field	4.5[b]	3.8[b]	0.7	0.0	0.7
		GC	21.2[a]	10.5[a]	10.7	4.5	6.2
	Roots	Field	2.6[b]	2.5[b]	0.1	0.0	0.1
		GC	20.8[a]	14.1[a]	6.7	1.9	4.8
Wheat	Grain	Field	23.2[ab]	16.7[b]	6.5	0.0	6.5
'Yecora		GC-RF[6]	25.8[a]	18.9[ab]	6.9	0.0	6.9
Rojo'		GC-LR[6]	25.2[a]	20.1[a]	5.1	0.0	5.1
		BPC	22.3[b]	18.9[a]	3.4	0.0	3.4
	Chaff	Field	8.9[b]	5.2[a]	3.7	0.0	3.7
		GC-RF	12.1[a]	5.4[b]	6.7	0.3	6.4
		GC-LR	13.2[a]	6.3[b]	6.9	0.1	6.8
		BPC	13.2[a]	8.0[a]	5.2	0.6	4.6
	Straw	Field	5.5[c]	3.4[c]	2.1	0.1	2.0
		GC-RF	14.4[b]	4.5[b]	9.9	3.6	6.3
		GC-LR	13.2[b]	3.8[c]	9.4	3.4	6.0
		BPC	23.3[a]	5.6[a]	17.7	13.0	4.7
	Roots	BPC	33.3	14.9	18.4	8.5	9.9
Potato	Tuber	Field	12.0[c]	6.5[a]	5.5	0.1	5.4
'Norland'		BPC-1[7]	15.8[b]	6.2[a]	9.5	0.1	9.5
		BPC-2[7]	20.0[a]	6.8[a]	13.2	0.1	13.1
	Vegetative[5]	Field	17.2[c]	12.8[a]	4.4	1.9	2.5
		BPC-1	24.3[b]	12.5[a]	11.8	8.0	3.8
		BPC-2	25.0[a]	11.3[a]	13.7	7.9	5.8
	Roots/ Stolons	Field	9.2[b]	6.7[b]	2.5	2.0	0.5
		BPC-1	26.6[a]	12.4[a]	14.2	9.3	4.9
		BPC-2	26.5[a]	13.0[a]	13.5	9.5	4.0

[1] Mean field values are averages of three plots, with at least two protein determinations from each field plot. Mean GC and BPC values from at least two protein determinations from each replicate.

[2] Means within each plant part having a common letter are not significantly different by t tests (unequal variances), p>0.05. The t-tests compared each controlled environment with the corresponding field environment.

[3] Calculated by difference between % protein from N (column 1) and % protein from TCA-precipitated N (column 2).

[4] Calculated by difference between % protein from total NPN (column 3) and % protein from nitrate N (column 4).

[5] Vegetative = leaves and stems.

[6,7] See Table 1 for explanation.

in essential amino acids have been observed for some field-grown cereal grains when higher N rates or late applications of N were used to increase grain protein concentrations /27/.

Mineral Content

The potassium (K), phosphorus (P), magnesium (Mg), and calcium (Ca) contents of rice and wheat grain and potato tuber generally were increased little to none in hydroponic-grown material compared to field-grown material, but these minerals typically increased greatly in inedible plant parts of hydroponic material (Table 5). The high apparent values for certain minerals in root material may be attributed to precipitation of nutrients onto roots and the difficulty of removing them with washing. The Ca content of potato tubers decreased in hydroponic conditions. This effect could be cause for concern because low Ca in potato tubers has been linked to internal brown spot and rapid deterioration during storage /28/.

Phosphorus level changes in plant material due to hydroponic growth conditions followed a pattern similar to nitrate levels, but P accumulated to some extent in edible plant parts (Table 5). High P levels in hydroponic solutions increased the P content of inedible plant parts more than in edible parts, and provide an incentive to avoid use of P levels in hydroponic solutions that are higher than necessary for maximum growth rates.

The Ca and P changes for inedible materials from controlled environments resulted in large decreases in the Ca/P ratio, which ideally is maintained at 1 for proper calcium absorption and retention in humans /29/. For example, Ca/P ratios of rice vegetative material from the field and growth chamber were 4.23 and 1.71, respectively. The Ca/P ratios of field-grown rice grain, wheat grain, and potato tuber were 0.03, 0.16, and 0.14, respectively, which are similar to USDA Handbook No. 8 values of 0.15, 0.13, and 0.13, respectively /17/. Because of low Ca levels in the typical edible parts of plant material other than green, leafy vegetables, it is difficult to achieve a high enough Ca/P ratio in a strict vegetarian diet. The higher Ca/P ratios of the typical inedible plant parts make their inclusion in a CELSS diet desirable, but the reduced Ca/P ratio of chamber-grown plant material is of concern. Reduced levels of P in hydroponic solutions could reduce the accumulation of P and thereby increase the Ca/P ratio. The reduced P level also may reduce concern about phytic acid, a storage form of P that accumulates in cereal grains and legume seeds /30/. Phytic acid reduces the bioavailability of elements such as Ca, iron (Fe), copper (Cu), and zinc (Zn) /30/, which could be of concern in a CELSS diet due to decreased levels of these elements in some parts of plants when grown in controlled environments compared to in the field (Table 6). For example, Fe, Cu, and Zn levels were greatly reduced in chamber-grown rice and potato vegetative material relative to field-grown material. Wheat grain Fe and Zn were reduced by about half in controlled environments compared to field conditions.

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TABLE 5 Content of Na, K, P, Mg, and Ca in rice, wheat, and potato grown in the field, growth chamber (GC), and biomass production chamber (BPC)

Crop	Plant Part	Condition	Mineral Content (ppm)				
			Na	K	P	Mg	Ca
Rice 'Ai-Nan-Tsao'	Grain	Field	----[1]	3,067	3,408	1,366	103
		GC	----	2,607	4,198	1,672	122
	Vegetative[2]	Field	90	23,072	945	2,152	3,996
		GC	234	44,738	4,680	4,830	7,995
	Roots	Field	339	7,791	434	2,010	2,962
		GC	349	18,463	5,176	1,040	3,566
Wheat 'Yecora Rojo'	Grain	Field	19	4,267	3,451	1,325	562
		GC-RF[3]	----	4,424	3,998	1,430	768
		GC-LR[3]	----	4,261	3,400	1,205	579
		BPC	----	5,521	4,808	1,911	354
	Chaff	Field	2	1,551	292	329	890
		GC-RF	86	12,650	3,154	1,246	2,541
		GC-LR	60	11,100	1,820	936	3,110
		BPC	24	19,306	4,257	3,372	3,230
	Straw	Field	123	27,314	680	872	3,134
		GC-RF	99	45,176	1,786	1,012	5,261
		GC-LR	80	41,100	1,090	856	4,368
		BPC	99	66,897	3,530	3,091	5,210
	Roots	BPC	118	45,611	2,428	1,176	1,846
Potato 'Norland'	Tuber	Field	28	26,872	3,267	1,410	470
		BPC-1[4]	6	25,735	3,314	1,571	146
		BPC-2[4]	5	29,140	4,867	1,924	281
	Vegetative[2]	Field	105	38,450	1,774	3,505	10,819
		BPC-1	6	79,174	3,118	5,746	12,969
		BPC-2	10	87,302	3,745	5,550	11,840
	Roots/ Stolons	Field	348	31,741	1,283	2,936	7,511
		BPC-1	133	48,219	2,989	7,115	5,446
		BPC-2	195	56,598	3,719	7,981	6,935

[1] Below detectable level.
[2] Vegetative = leaves and stems.
[3,4] See Table 1 for explanation.

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TABLE 6 Content of Mo, Zn, B, Mn, Fe, and Cu in rice, wheat, and potato grown in the field, growth chamber (GC), and biomass production chamber (BPC)

Crop	Plant Part	Condition	Mineral Content (ppm)					
			Mo	Zn	B	Mn	Fe	Cu
Rice 'Ai-Nan-Tsao'	Grain	Field	----[1]	39	----	19	4	6
		GC	----	42	----	10	8	6
	Vegetative[2]	Field	----	101	2	562	437	30
		GC	3	26	30	97	174	20
	Roots	Field	1	127	4	447	4,860	45
		GC	2	30	18	19	7,843	60
Wheat 'Yecora Rojo'	Grain	Field	----	50	----	34	37	5
		GC-RF[3]	----	30	----	38	18	8
		GC-LR[3]	----	26	----	21	14	6
		BPC	----	25	----	40	26	5
	Chaff	Field	----	5	----	7	79	2
		GC-RF	1	10	31	36	53	6
		GC-LR	----	11	26	18	76	5
		BPC	----	13	58	102	108	5
	Straw	Field	----	21	----	17	198	4
		GC-RF	3	14	23	18	103	8
		GC-LR	3	14	30	15	79	6
		BPC	----	8	93	58	162	5
	Roots	BPC	----	15	48	35	840	56
Potato 'Norland'	Tuber	Field	----	27	4	14	104	7
		BPC-1[4]	----	11	7	10	42	6
		BPC-2[4]	1	24	6	13	37	10
	Vegetative[2]	Field	----	114	22	217	2,353	23
		BPC-1	----	14	66	133	351	7
		BPC-2	----	12	53	141	365	8
	Roots	Field	----	129	12	265	4,056	25
		BPC-1	----	29	28	1,069	983	206
		BPC-2	1	21	27	1,340	1,116	279

[1] Below detectable level.
[2] Vegetative = leaves and stems.
[3,4] See Table 1 for explanation.

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